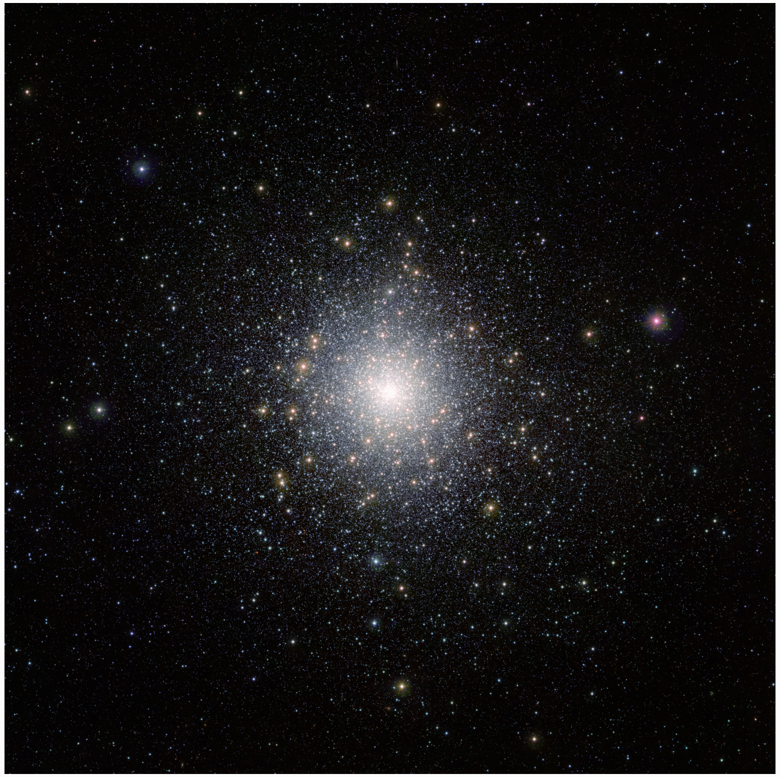
Globular clusters
Corinne Charbonnel – University of Geneva



Part I – GC general properties

Part II – Chemical dissection and multiple stellar populations in GCs
Towards a new paradigm

Part III – The evolution of the multiple stellar populations in GCs

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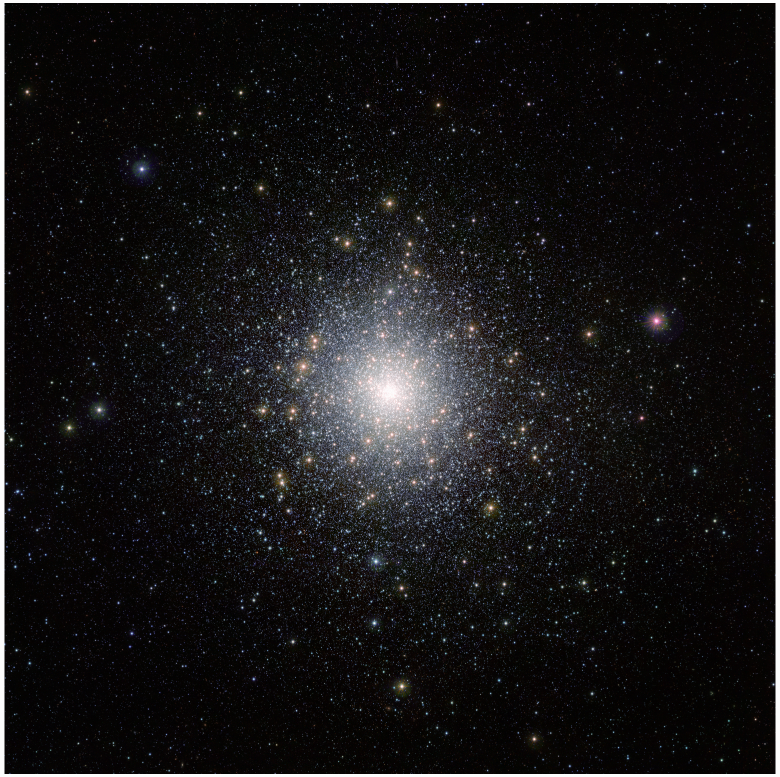
FACULTÉ DES SCIENCES
Département d'astronomie

Multiple stellar populations and their evolution in globular clusters



Part II – Multiple Populations
Towards a new paradigm

- ✓ Heavy elements in GCs
- ✓ Light elements and the presence of multiple populations
- ✓ Photometric signatures
- ✓ Potential polluters
- ✓ GC initial masses
- ✓ Early dynamical and chemical evolution
  Towards a global scenario
- ✓ Contribution to the Galactic halo

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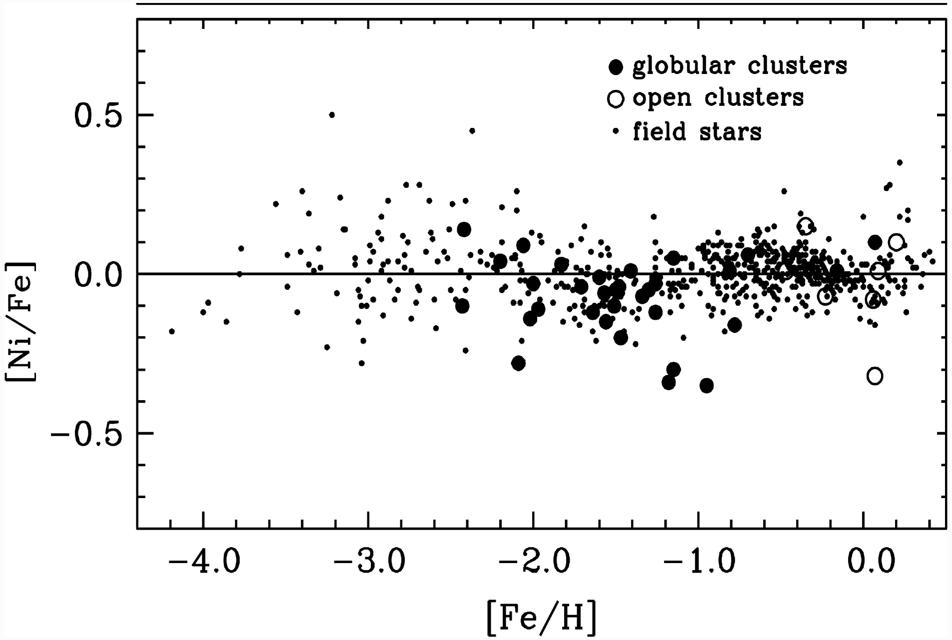
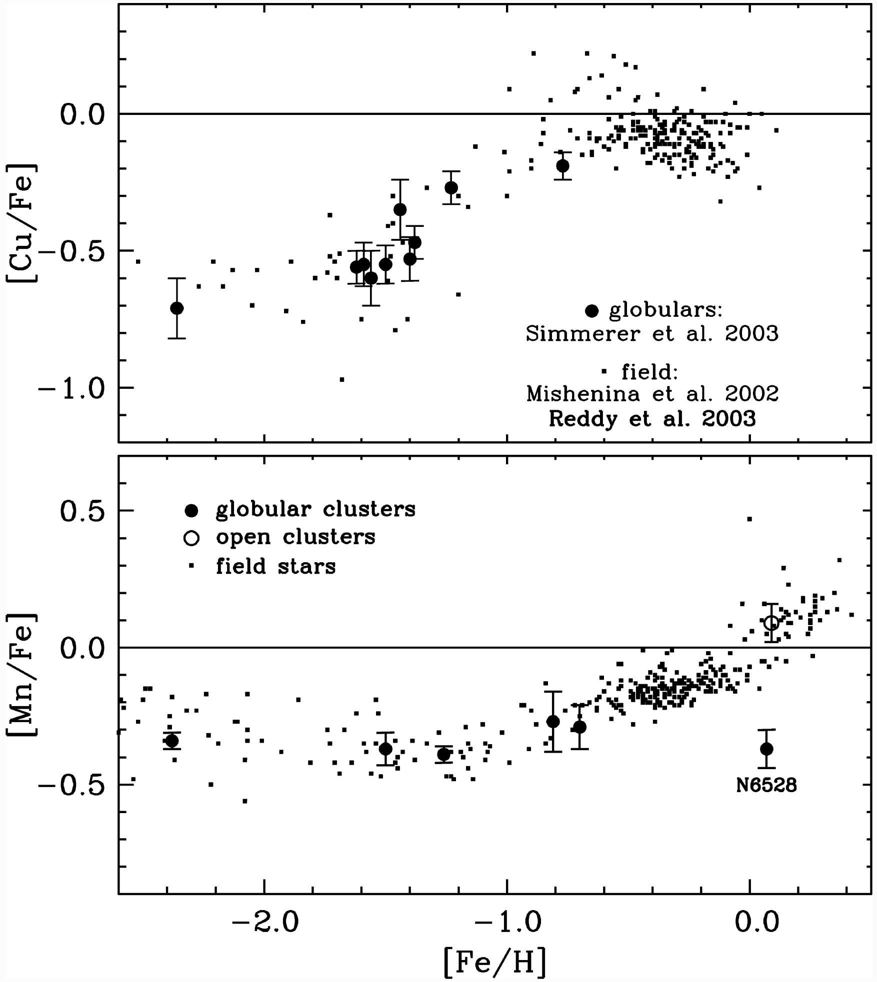
Milky Way GCs – Iron-peak elements

\# Ni, Cu, Mn

- ✓ Pre-galatic enrichment
- ✓ Same trends as field stars



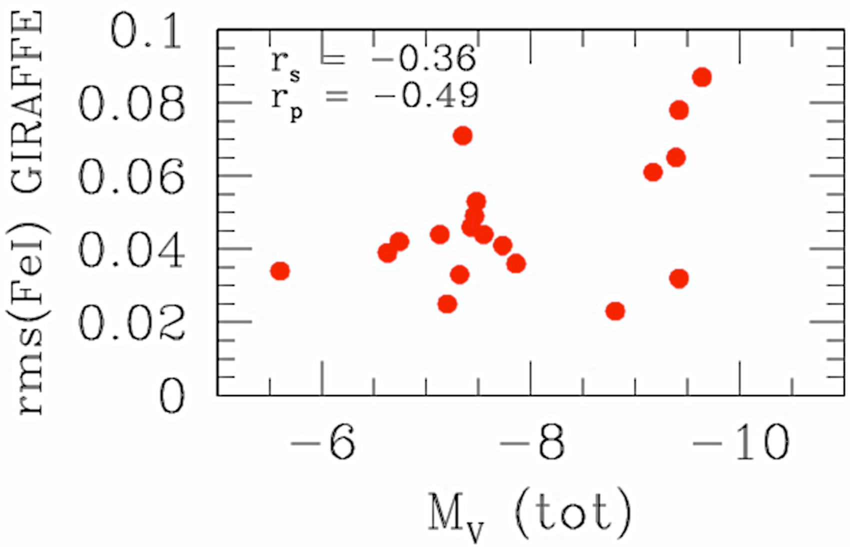


Carretta *et al.* (09)

See also e.g. Harris & Pudritz (94) - James *et al.* (04)

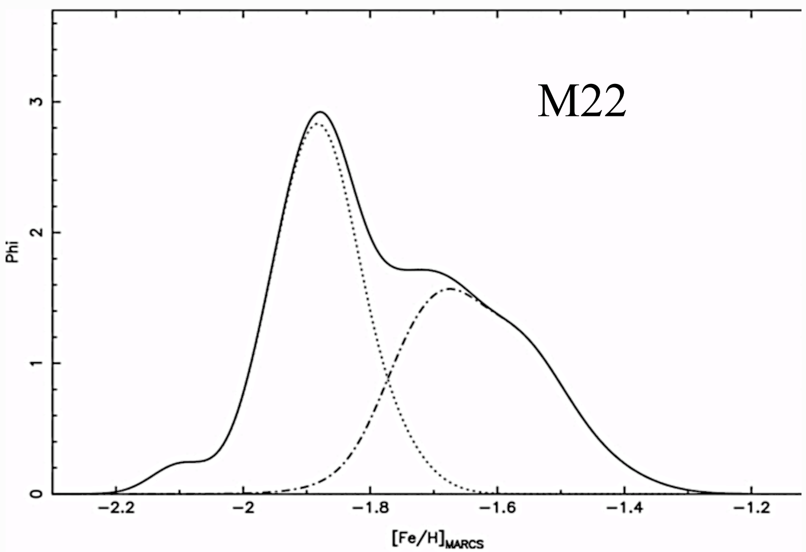
Milky Way GCs – Iron-peak elements

✓ Most GGCs are mono-metallic → **No self-enrichment**

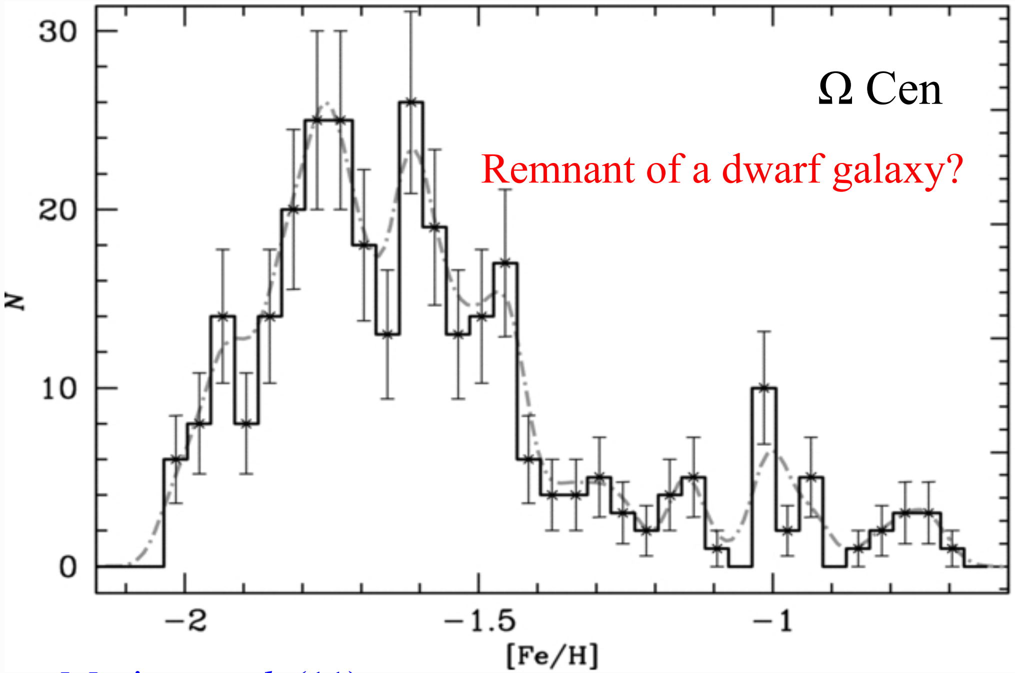


Observed intrinsic dispersion in Fe
from GIRAFFE spectra
vs visual total magnitude of 19 GGCs
Carretta *et al.* (09)

✓ *Rare exceptions: The most massive GGCs*
ΩCen, M54, M22, NGC 3201, NGC 1851

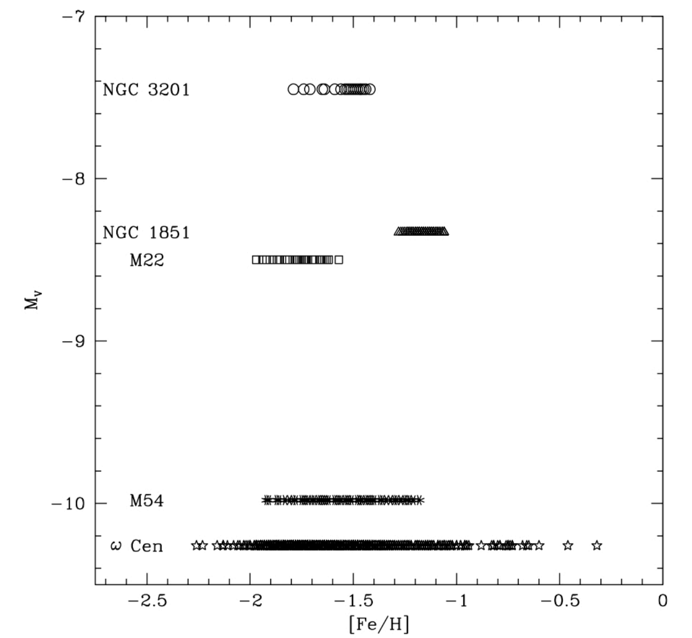


Da Costa *et al.* (09)

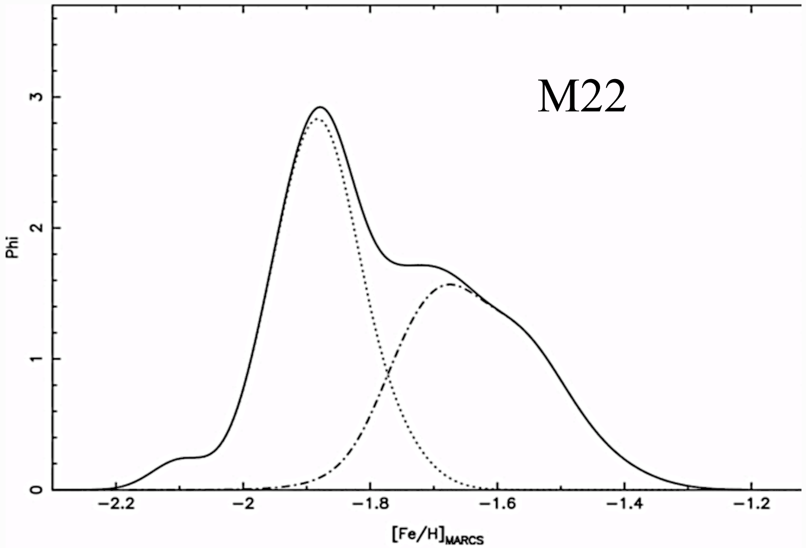


Marino *et al.* (11)

Milky Way GCs – Iron-peak elements



Simmerrer *et al.* (13)



Da Costa *et al.* (09)

✓ *Rare exceptions: The most massive GGCs*
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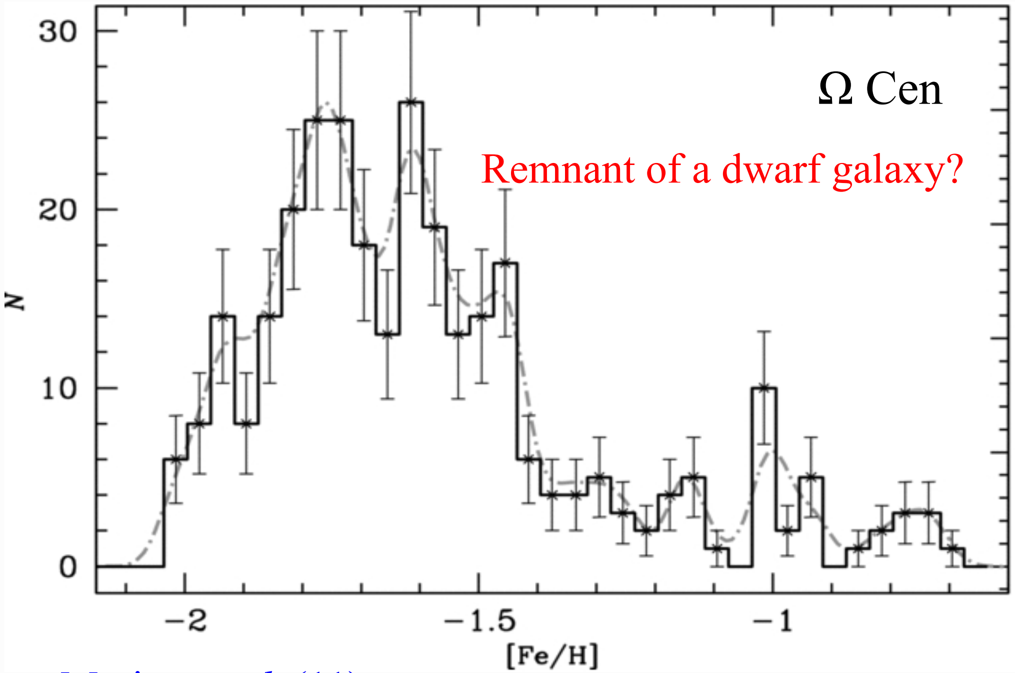
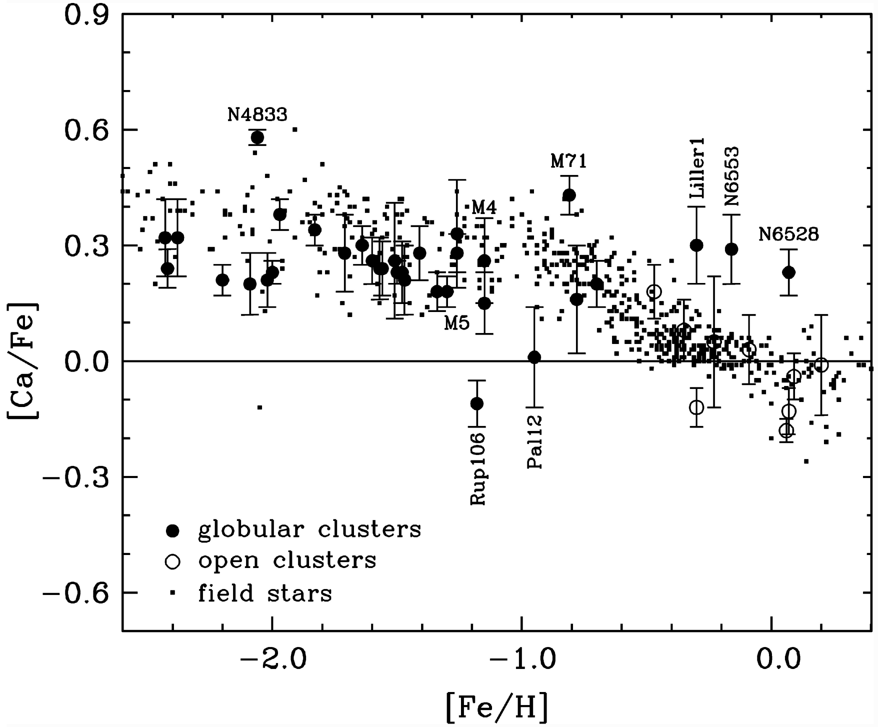


Marino *et al.* (11)

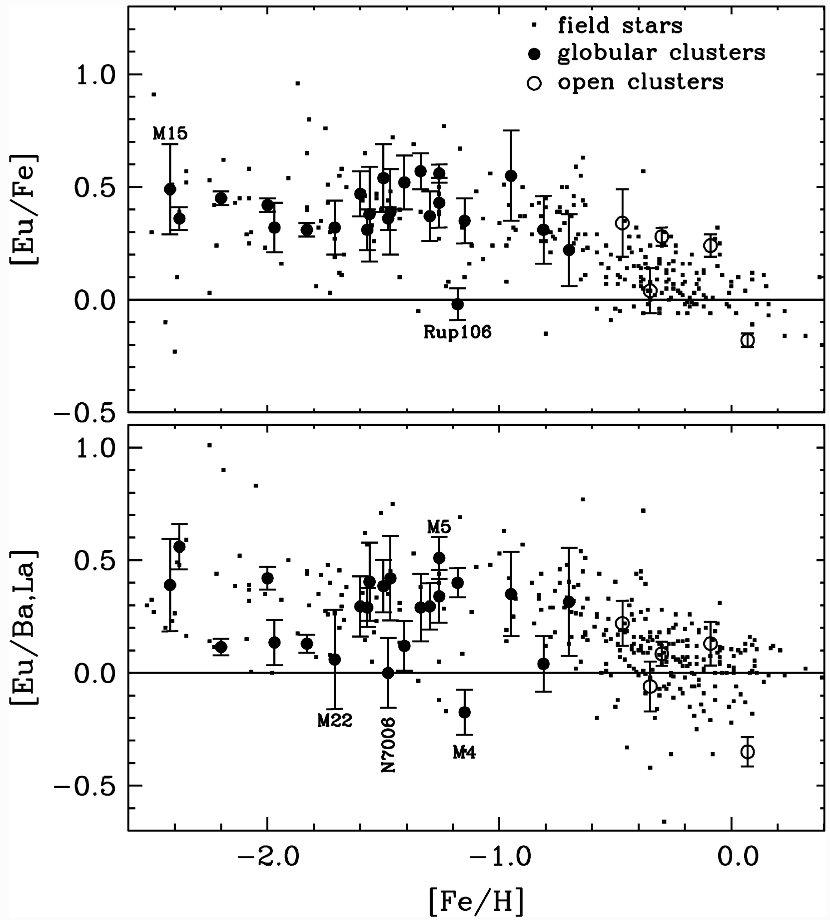
Milky Way GCs – Alpha- and neutron-capture elements

- ✓ Same trends as field stars
- ✓ No internal scatter

(exceptions: ΩCen, M22, NGC 1851)



Alpha-elements (Si, Ca)



Neutron-capture elements (Ba, La, Eu)

Gratton *et al.* (04 ARAA)
See also James *et al.* (04)

Chemical dissection of Galactic GCs

Alpha-elements (Si, Ca)
Neutron-capture elements (Ba, La, Eu)
Fe-peak elements (Ni, Cu, Mn)

- No internal scatter
  (exceptions: ΩCen, M54, 22, NGC 3201, 1851)
- Same trends as with Z field *

GC heavy metals must come from pre-enrichment during the building and the chemical evolution of the halo (i.e., same as halo field stars)

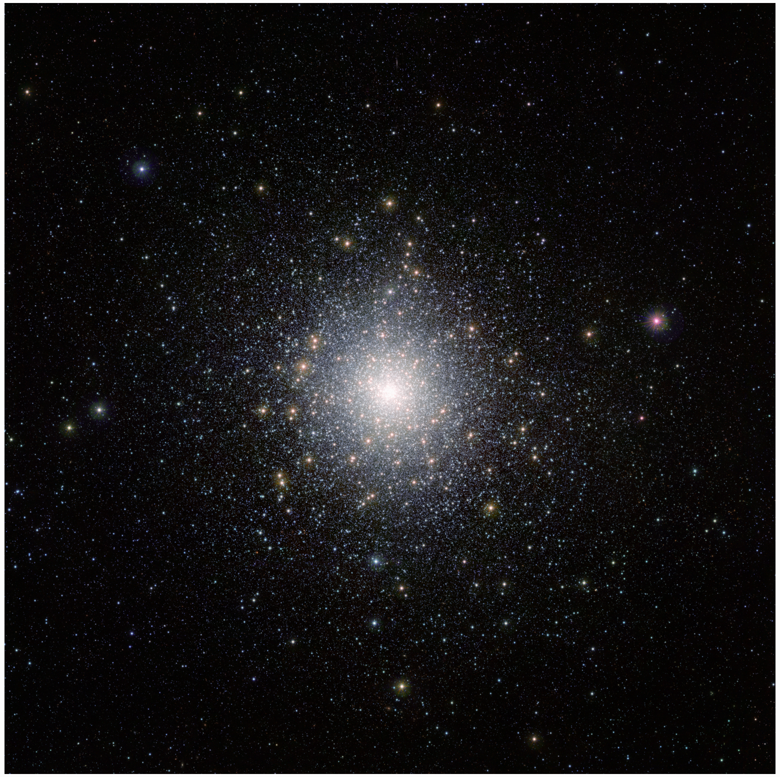
Harris & Pudritz (94) - James *et al.* (04)

No self-enrichement (except in the most massive GCs)

Light elements (C to Al)
Large star-to-star abundance variations
C-N, O-Na, Mg-Al, F-Na, Li-Na anticorrelations

Reviews by Gratton *et al.* (04 ARAA)
& Sneden (05 IAU 228)
See also James *et al.* (04)

Multiple stellar populations and their evolution in globular clusters



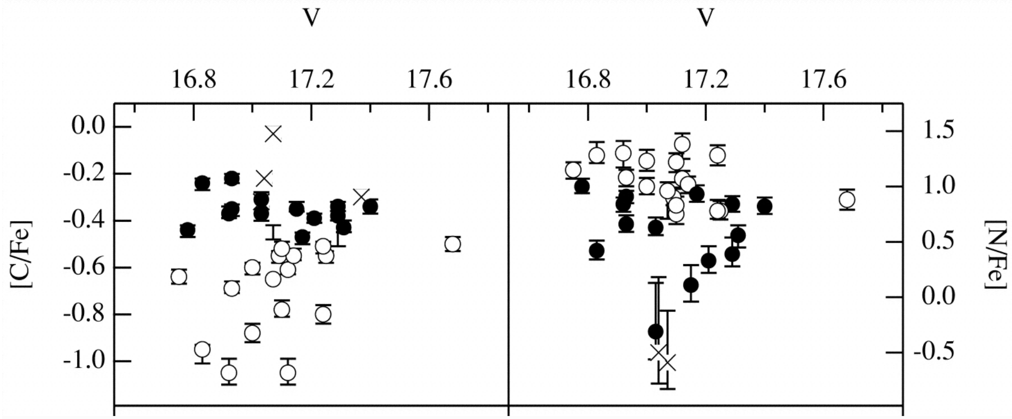
Part II – Multiple Populations
Towards a new paradigm

- ✓ **Heavy elements in GCs**
- ✓ **Light elements and the presence of multiple populations**
- ✓ **Photometric signatures**
- ✓ **Potential polluters**
- ✓ **GC initial masses**
- ✓ **Early dynamical and chemical evolution**
  Towards a global scenario
- ✓ **Contribution to the Galactic halo**

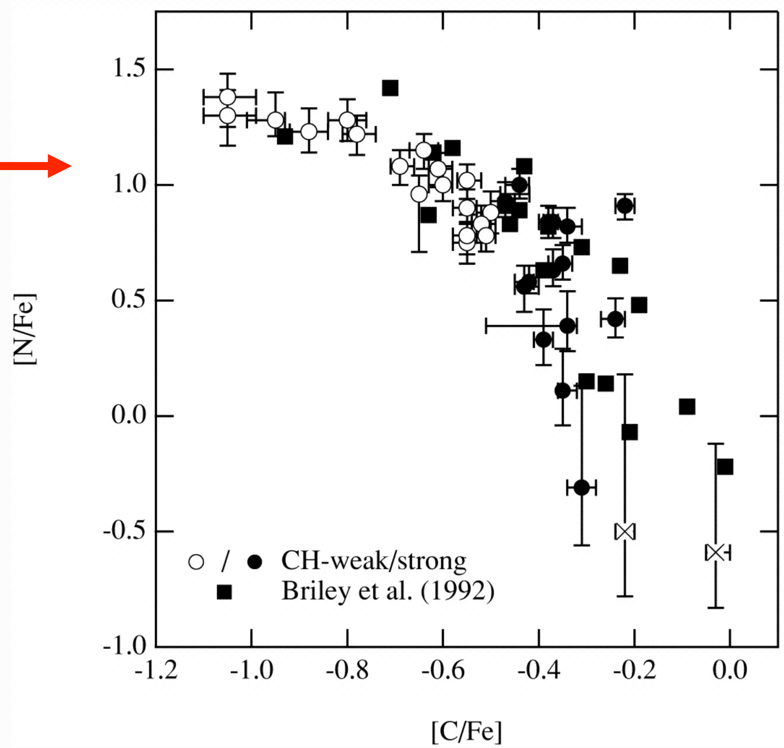
C-N anticorrelation

M15 subgiants [Fe/H] ~ -1.21

Large scatter at all luminosities
and C-N anticorrelation



CN and CH molecular bands



CN processing
of stellar material

Cohen *et al.* (2002)

O-Na anticorrelation in Galactic globular clusters
A general property

"Anomalous",
[O/Na] ~ -2

2[d] generation/
population

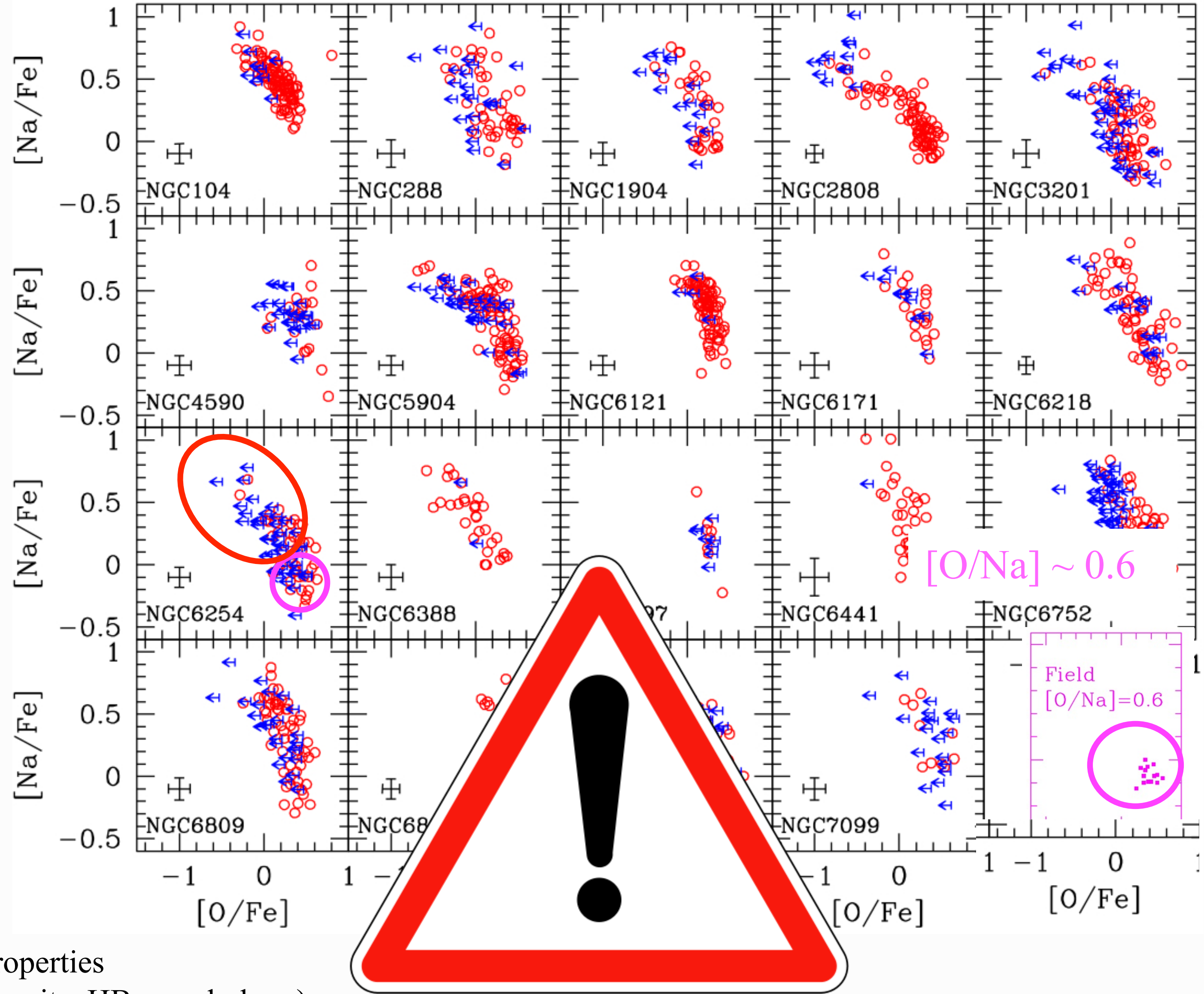
~ 70±7 %

"Normal" ,
[O/Na] ~ 0.6
formed out of
original GC material

1[st] generation/
population

~ 30±7 %

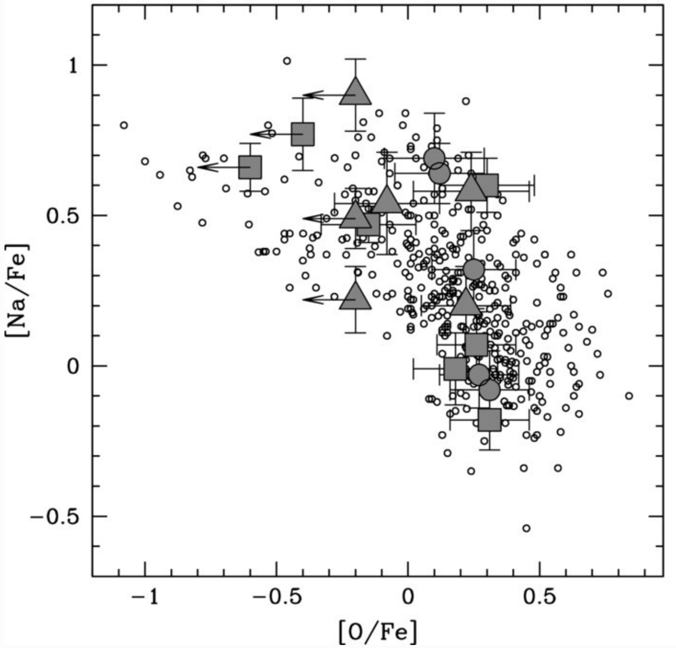
Prantzos & Charbonnel (06)



MW GCs with
- -2.16 ≤ [Fe/H] ≤+0.07
- a large range of physical properties
  (≠ total M, concentration, density, HB morphology)
- disk and halo population

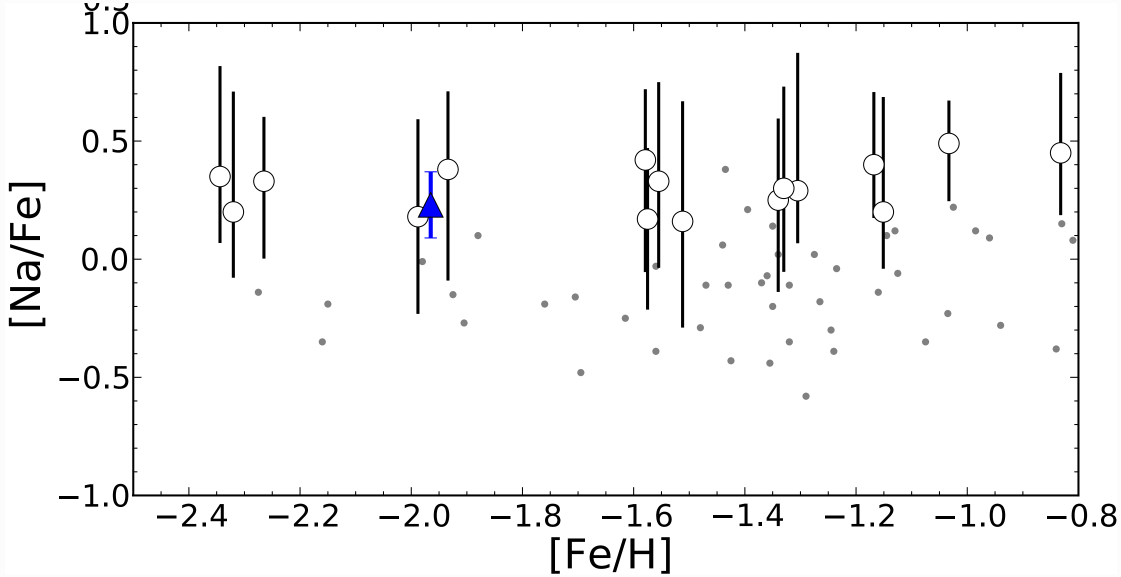
Carretta *et al.* (10, VII)

O-Na anticorrelation in GCs of the local group



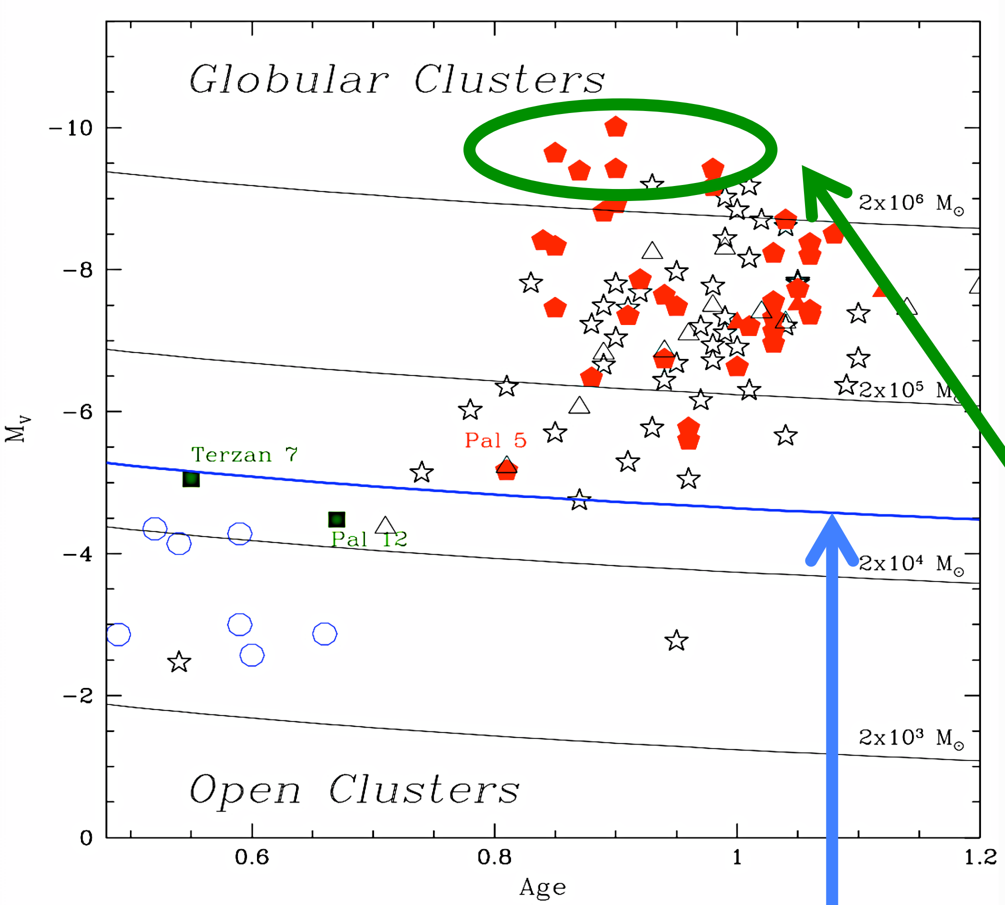
3 old LMC clusters:
NGC 1786, 2210, 2257
Mucciarelli *et al.* (09)

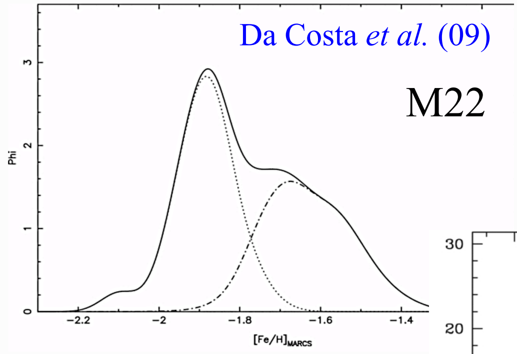
Evidence of Na-enrichment in GCs of the local group

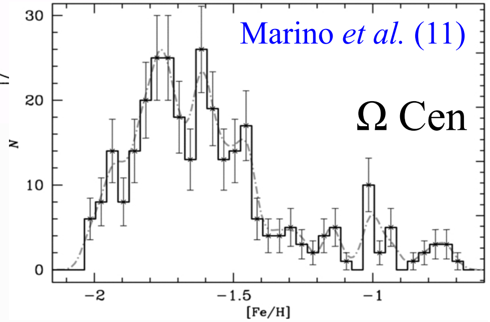


GC in the dwarf WLM galaxy using synthetic integrated-light model spectra
Mean Na for GGCs, and Na in field stars
Larsen *et al.* (14)

O-Na anticorrelation







Minimum present-day mass for a star cluster to exhibit [Fe/H] dispersion

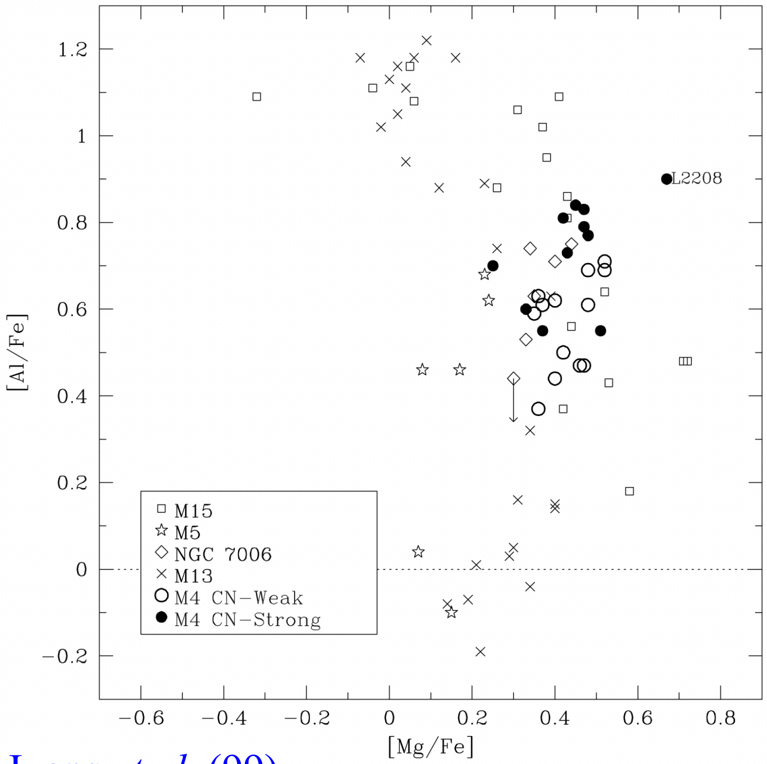
MW and LMC GCs with anticorrelation
Sagittarius dSph GC without anticorrelation
Old open clusters
No or too few data

Carretta *et al.* (10)

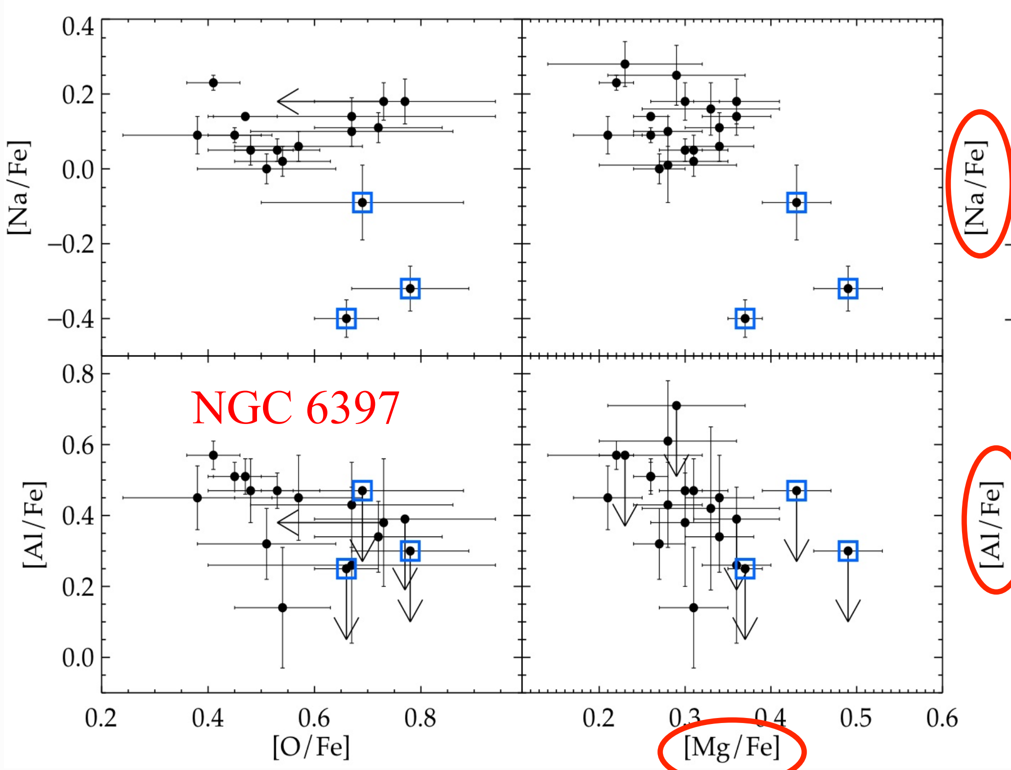
Minimum present-day mass for a star cluster to exhibit the O-Na anticorrelation (but no [Fe/H] dispersion)

Universal, intrinsic property of GCs

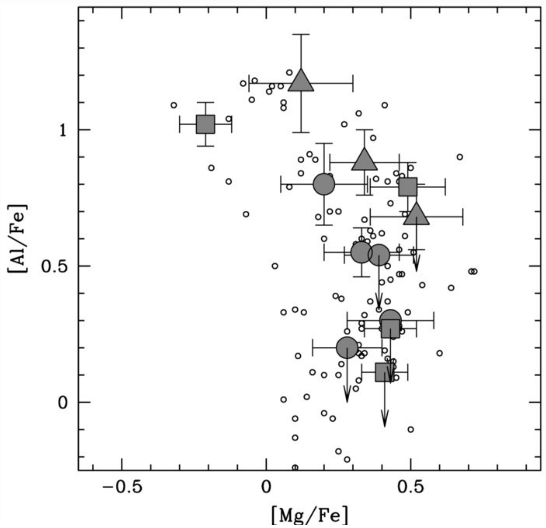
Mg-Al anticorrelation



Ivans *et al.* (99)



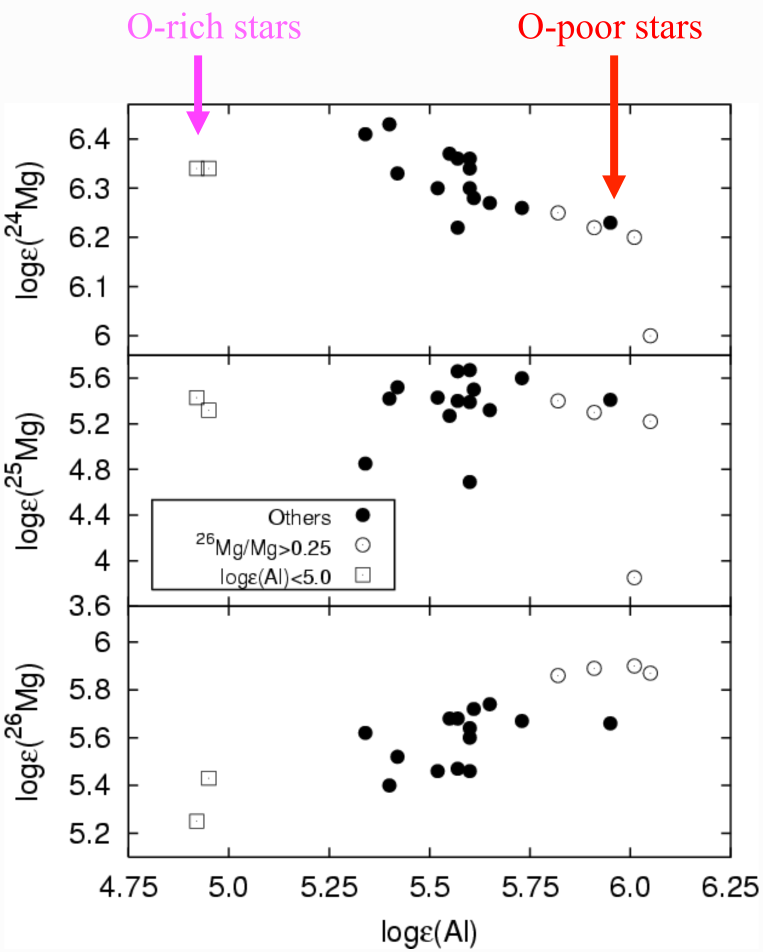
Lind, Charbonnel, Decressin,
Primas, Asplund & Grundahl (11)



Observed both in bright giants and faint turnoff members
Ramirez & Cohen (2002), Gratton *et al.* (01), Grundhal *et al.* (03)

3 old LMC clusters:
NGC 1786, 2210, 2257
Mucciarelli *et al.* (11)

Mg-Al anticorrelation and Mg isotopes



NGC 6752

[Fe/H] = -1.42

Yong *et al.* (03)

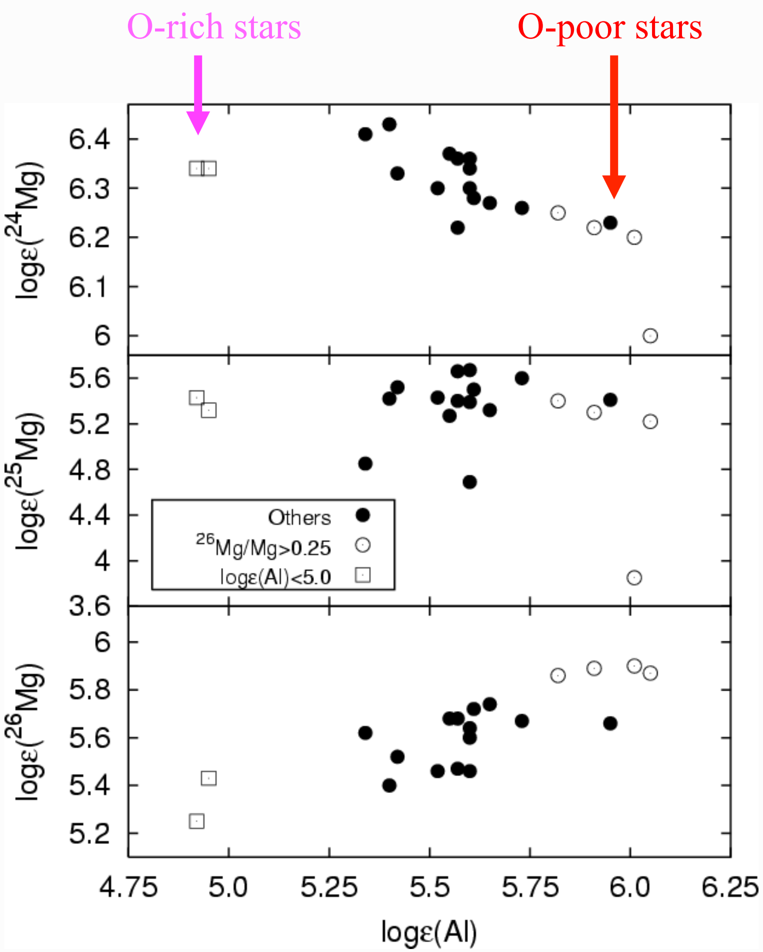
^{24}Mg declines slightly
with increasing Al abundance
Shetrone (96)

^{25} Mg ~ constant
over the 1.1 dex range in Al abundance

^{26}Mg is well correlated with Al abundance,
with a total spread of a factor of ~ 4

Same in M3 and M71
Yong *et al.* (05)

Mg-Al anticorrelation and Mg isotopes



NGC 6752

[Fe/H] = -1.42

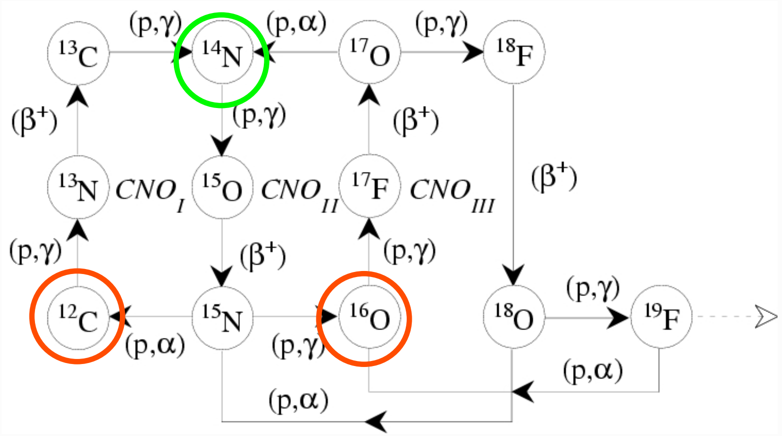
Yong *et al.* (03)

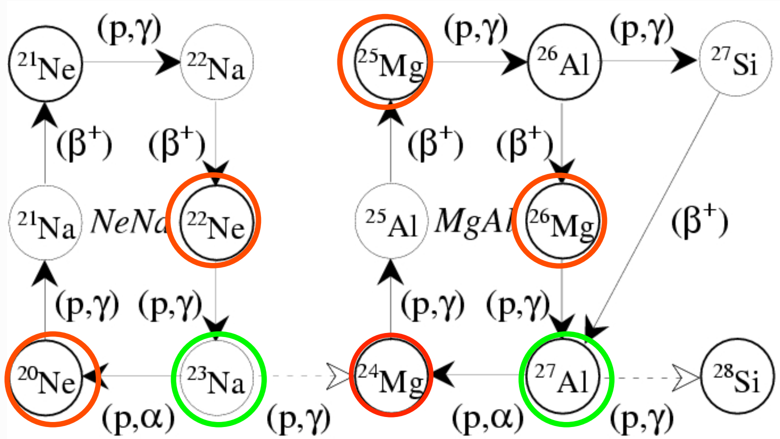
« To the extent
that it's possible,
it is the isotopes
that keep
the theorists honest »
Dave Arnett

C-N, O-Na, Mg-Al anticorrelations

H-burning through CNO, NeNa, MgAl at T ~ 72 to 78 MK

Prantzos, Charbonnel & Iliadis (07)





T ≥ 15 x 10^6 K : CN

T ≥ 25 x 10^6 K : CNO, ^{22}Ne → ^{23}Na

T ≥ 40 x 10^6 K : CNO, ^{20}Ne → ^{23}Na

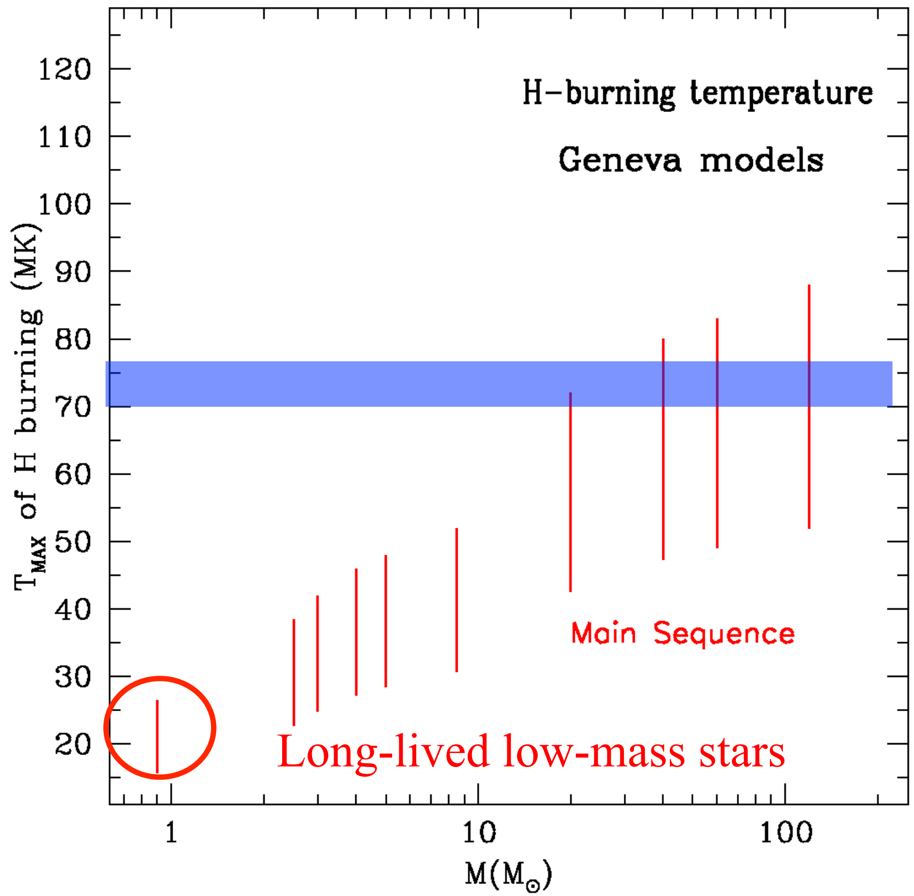
^{25,26}Mg → ^{26}Al, ^{27}Al

T ≥ 70 x 10^6 K : ^{24}Mg (and ^{25,26}Mg) → ^{26}Al, ^{27}Al

C-N, O-Na, Mg-Al anticorrelations

H-burning through CNO, NeNa, MgAl at T ~ 72 to 78 MK

Prantzos, Charbonnel & Iliadis (07)

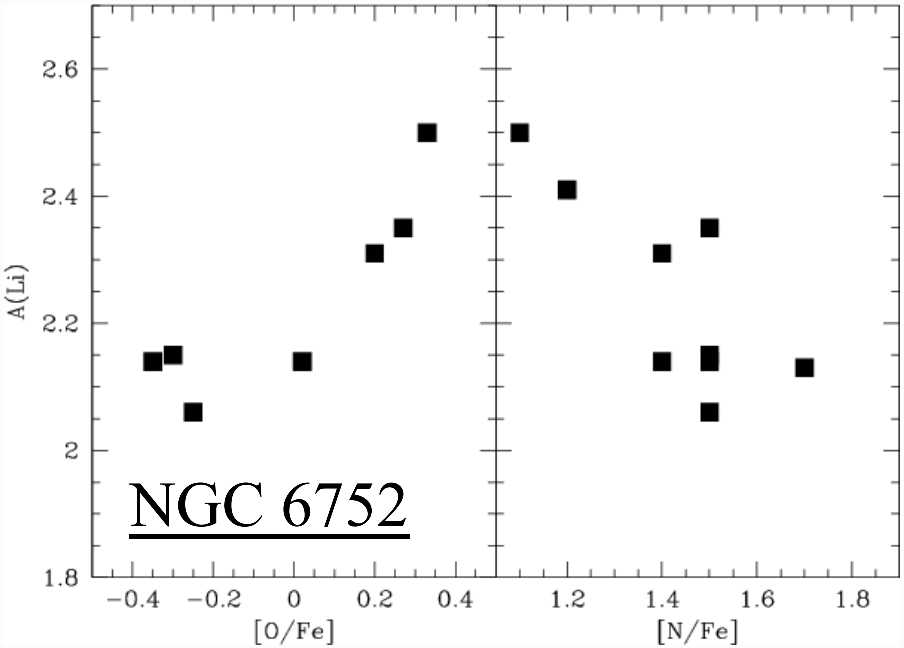


The observed patterns *pre-existed*
in the material out of which
the presently surviving stars formed

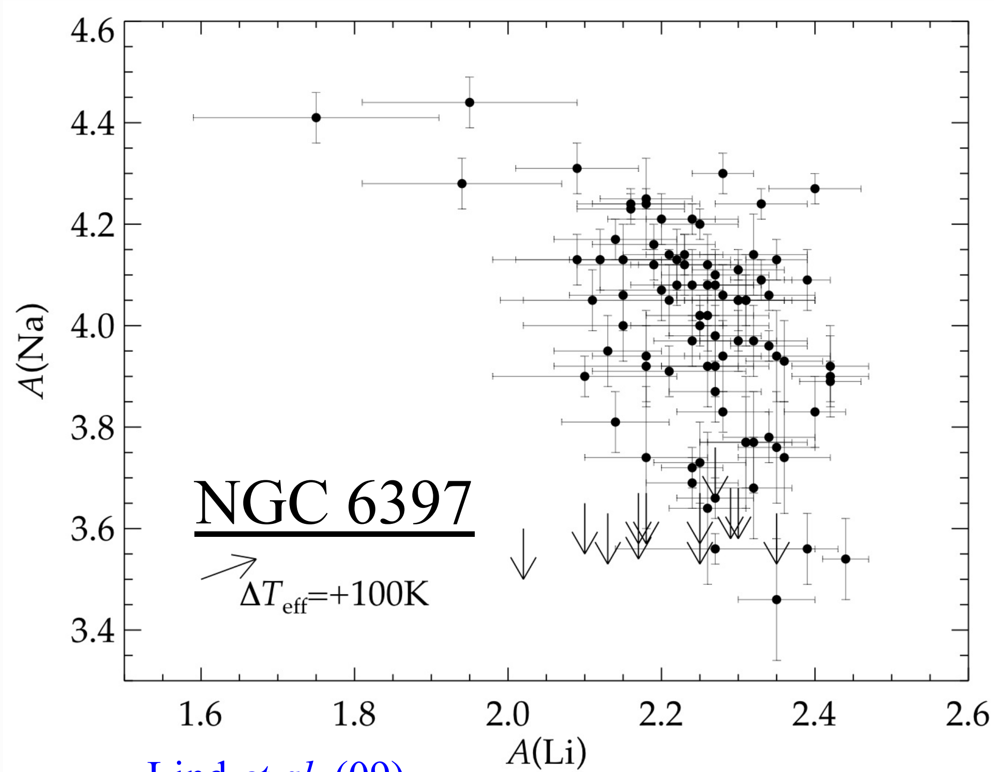
Implies *pollution of the intra-cluster gas*
by a first generation of *more massive*
rapidly evolving *stars*
in which H burns at ~ 72-78MK!
→ *Formation of second population of stars*

Lithium abundance variations – Li-Na anticorrelation

Turnoff stars



Pasquini *et al.* (05)

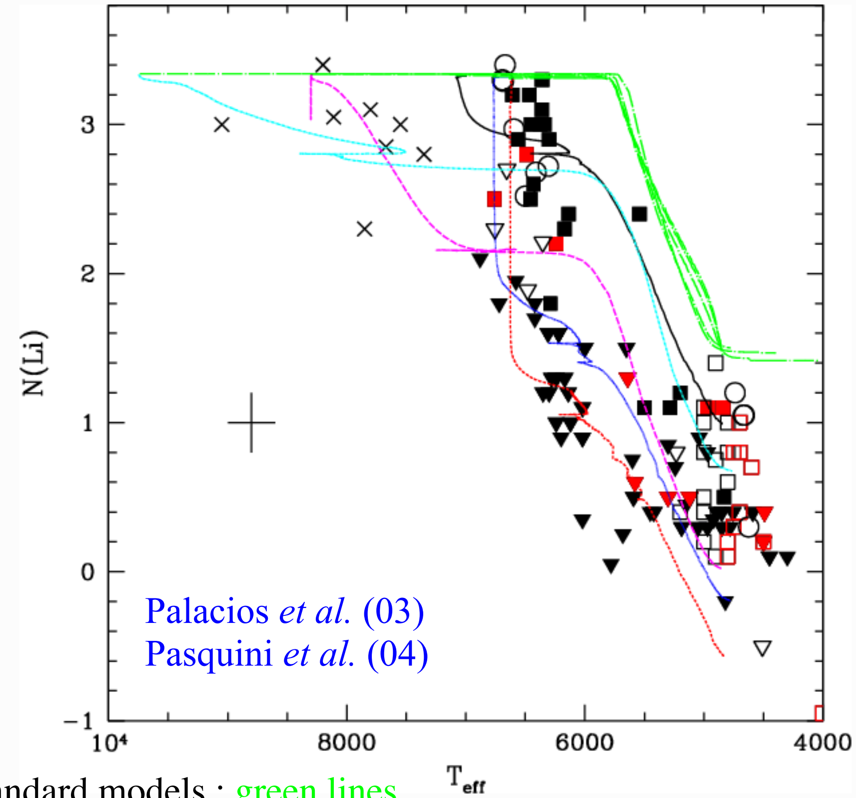


Lind *et al.* (09)

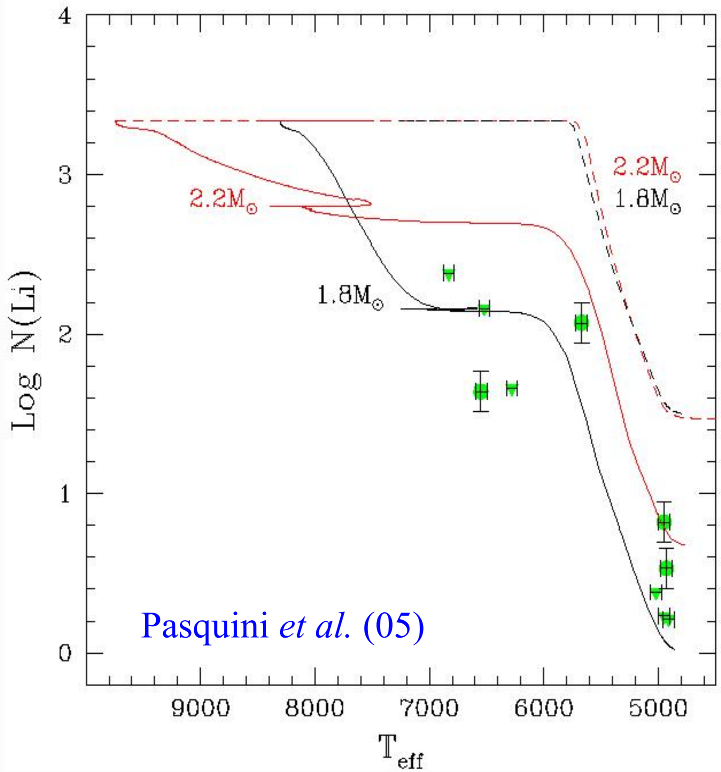
Li is a very fragile element (burns at ~ 2.5 MK)
Its presence implies *dilution of polluted matter with pristine intra-cluster gas*

Internal transport processes (rotation, diffusion, …)
in stellar interiors are known to affect the surface abundance of Li
(e.g., the Sun, open clusters, …)

Rotation-induced mixing and Li depletion in low-mass stars



Standard models : green lines
Rotating models of various M_* : other colored lines
Observations : Field and
open cluster evolved stars
Lèbre *et al*. (99), Wallerstein *et al*. (94), Gilroy (89)
Pasquini *et al*. (01), Burkhart & Coupry (98, 00)

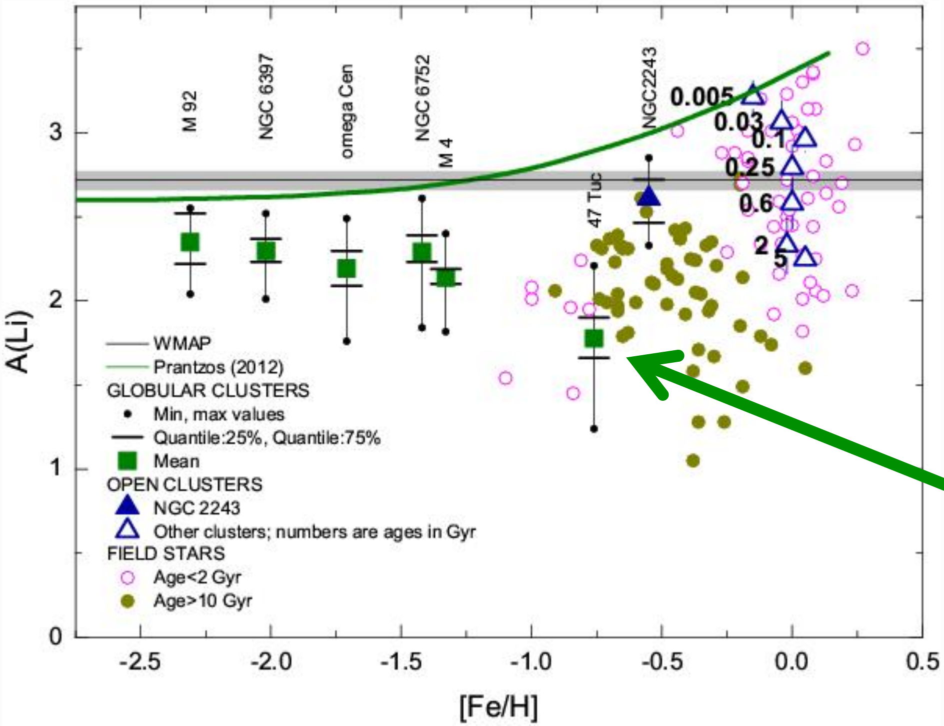


Standard models : dotted lines
Rotating models : full lines (Palacios *et al*. 03)
Observations : IC 4651 evolved stars

Internal transport processes (rotation, diffusion, …) in stars with different He content are also expected to affect the surface abundance of Li (e.g., the Sun)

Wednesday lecture

Lithium abundance variations – Li-Na anticorrelation



✓ The mean lithium abundance of the metal-poor globular clusters traces well the Spite Plateau

→ Very similar internal processes (transport of angular momentum and chemicals), solid-body rotators?

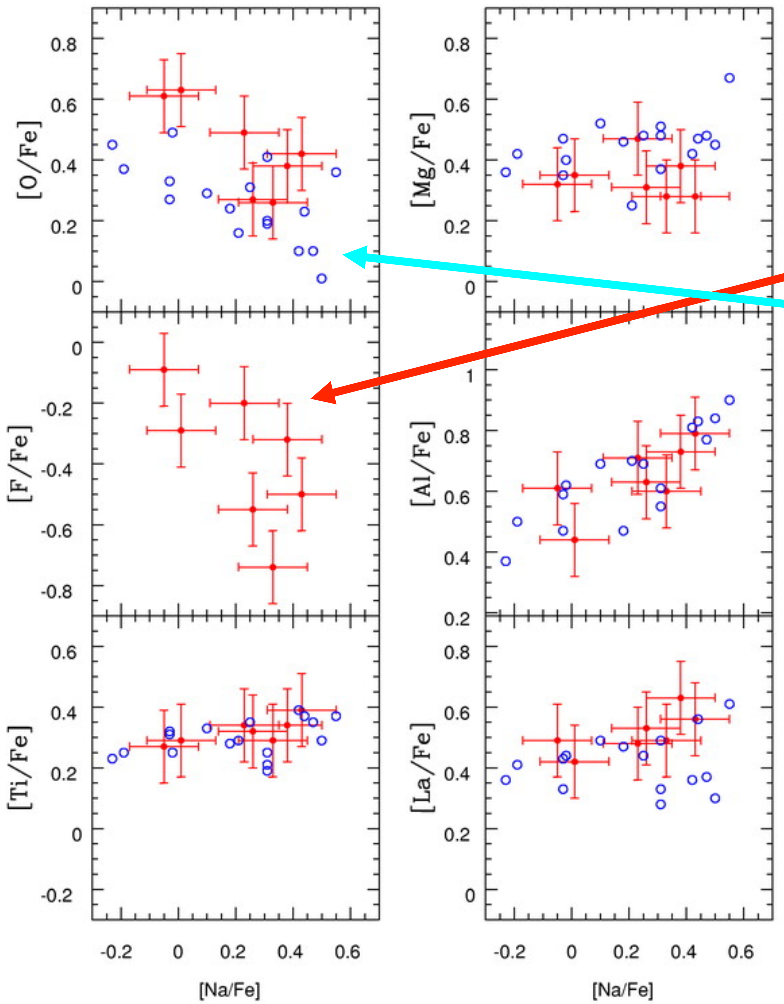
✓ 47 Tuc has lower mean lithium abundance and higher dispersion than other globular clusters; these values are compatible with lithium abundances observed in the field stars at the same metallicity and older than 12 Gyr

→ Different turnoff mass (different Z), deeper stellar convective envelope, more spread induced by e.g. rotation

Dobrovolskas *et al.* (2014)

Fluorine abundance variations

M4 (NGC 6121) Smith *et al.* (2005)



Abundance of ^{19}F

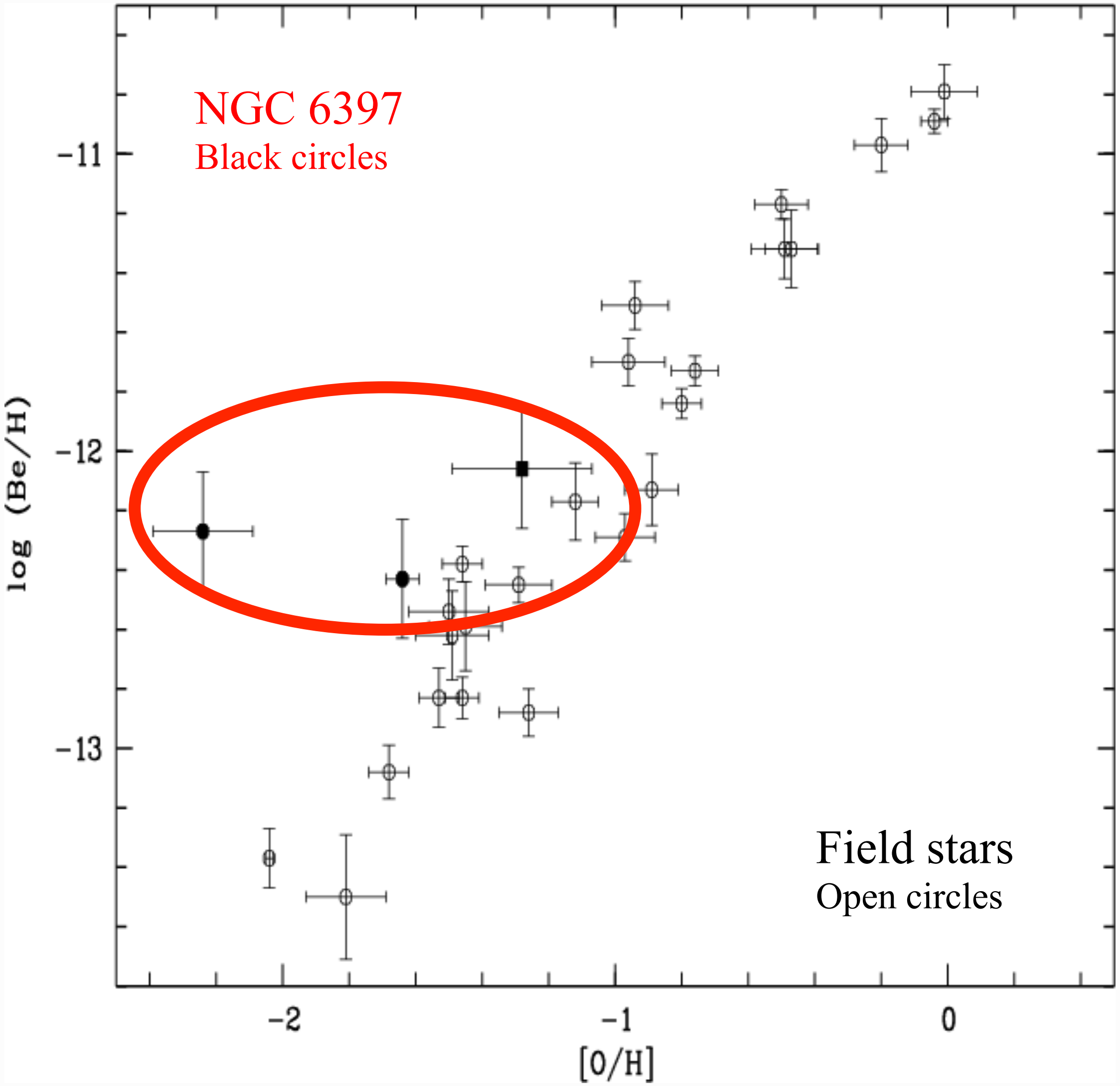
- varies by more than a factor of 6
- anticorrelated with Na and Al variations
- correlated with O variations

Open blue : M4 stars from Ivans et al (99)
Filled red : M4 stars with F determinations

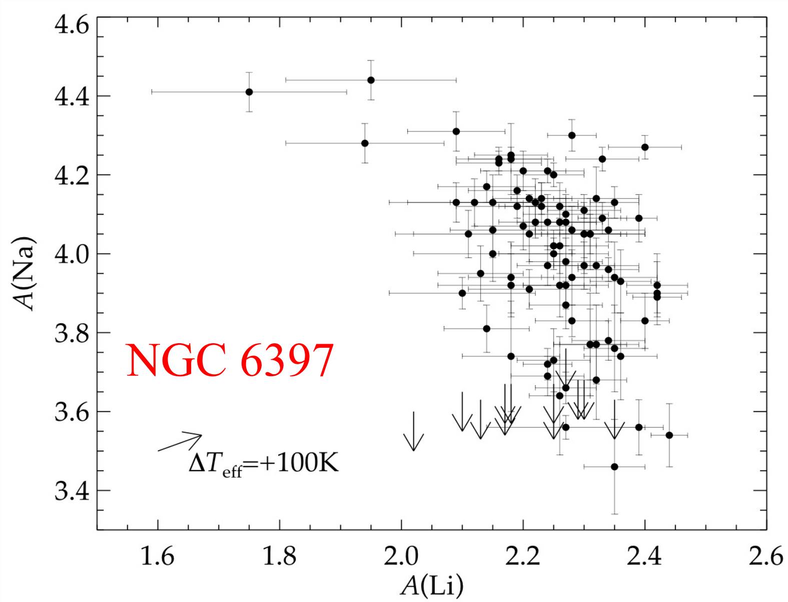
Beryllium (spallation)

- ✓ Be burns at ~ 3.5 MK
- ✓ Be is **not** produced in stars!

Dilution
Cosmic Ray nucleosynthesis in the young GCs?



Pasquini *et al.* (07)



Lind, Primas, Charbonnel, Grundahl & Asplund (09)

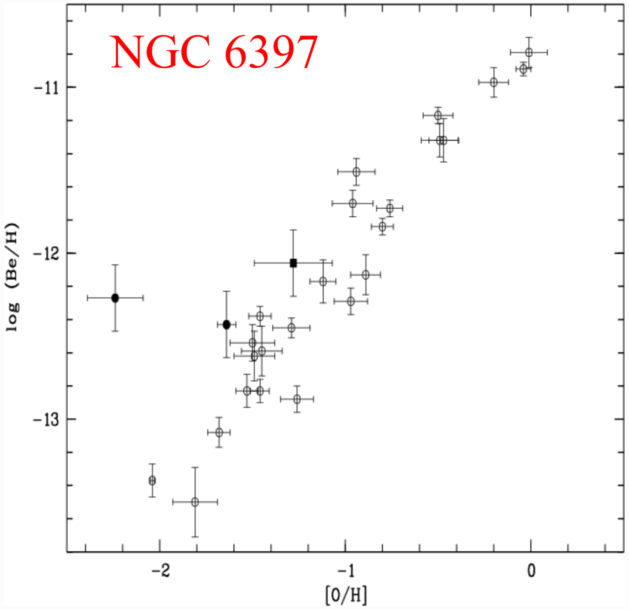
O-Na, Mg-Al anticorrelations

H-burning (CNO, NeNa, MgAl) at T ~ 72 to 78 MK

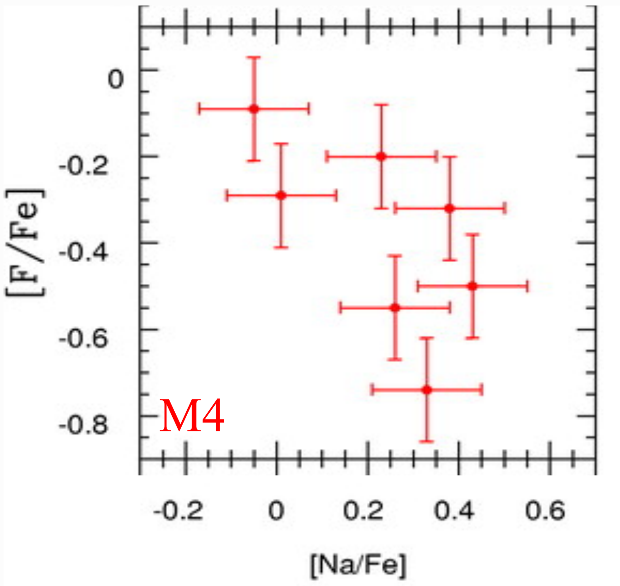
Li, F and Be

H-burning ashes devoid of light elements (LiBeBF)

→ *2G stars form from*
H-burning ashes mixed with pristine gas



Pasquini *et al.* (07)



Smith *et al.* (05)

~ 50 % of original gas (LiBeBF-rich)
& 50 % of stellar ejecta (LiBeBF-free)

C-N, O-Na, Mg-Al, F-Na, Li-Na anticorrelations
[(C+N+O)] ~ constant within experimental errors
[Fe/H] constant

H-burning through CNO, NeNa, MgAl
H-burning ashes mixed with pristine gas
} → 2d generation

No recycling of He-burning products

No recycling of supernovae ejecta,
except in some rare (most massive) cases (e.g., Ω Cen or M22)